Coral Reefs (1986) 5:55–62

Coral Reefs

Catastrophic impact of hurricanes on atoll outer reef slopes in the Tuamotu (French Polynesia)

Mireille L. Harmelin-Vivien [1] and Pierre Laboute [2]

[1] Centre d'Océanologie de Marseille, Station Marine d'Endoume, F-13007 Marseille, France, and Centre de l'Environnement de Moorea, Museum National d'Histoire Naturelle et Ecole Pratique des Hautes Etudes, BP 12, Moorea, Polynésie Française

[2] Centre O.R.S.T.O.M. de Tahiti, BP 529, Papeete, Tahiti, Polynésie Française

Accepted 12 May 1986

Abstract. Underwater effects on coral reefs of the six hurricanes which ravaged French Polynesia between December 82 and April 83 were observed by SCUBA diving around high islands and atolls during September and October 1983. Special attention was paid to Tikehau atoll reef formations (Tuamotu archipelago) where quantitative studies on scleractinians, cryptofauna and fishes were conducted in 1982 immediatly prior to the hurricanes. On outer reef slopes coral destruction, varying from 50 to 100%, was a function of depth. Upper slope coral communities composed of small colonies well adapted to high energy level environments, suffered less than deeper formations. However, there is a narrow erosional trough in this zone at a depth of 6 m that was probably the result of storm-wave action (plunge point). Coral destruction was spectacular at depths greater than 12 m: 60 to 80% between 12 m and 30 m and 100% beyond 35 m, whereas earlier living coral coverage ranged from 60 to 75% in these zones. The outer slope was transformed into a scree zone covered with coarse sand and dead coral rubble. Dives on different sites around steep outer slopes (>45°) of the atolls and more gentle slopes (<25°) of some parts of the high islands permitted the formulation of an explanatory hypothesis: direct coral destruction by hurricane-induced waves occurred between the surface and 18–20 m; on low-angle slopes broken colonies were thrown up on reef flats and beaches; on steep slopes avalanches destroyed much of the living corals and left scree slopes of rubble and sand.

Introduction

Storm induced catastrophic effects have been described as a major geomorphological agent for tropical islands and reefs (Stoddart 1969, 1970; Endean 1976). Most of the studies carried out on the effects of cyclones, typhoons or hurricanes on coral reefs referred to shallow water areas, reef flats and littoral zones (Stephenson et al. 1958; Blumenstock 1961; Stoddart 1962, 1963, 1965; Ogg and Koslow 1978; Rogers et al. 1982). Except for recent studies on the effects of the typhoon Pamela on the coral reefs of Guam (Randall and Eldredge 1977) and on the hurricane Allen's impact on Jamaican coral reefs (Woodley et al. 1981; Kjerfve et al. 1986), little attention has been paid to hurricane impact on outer reef slope formations. Previous investigations have indicated that damage caused by hurricanes was usually localized and restricted to shallow water areas (Banner 1961; Stoddart 1962, 1963; Glynn et al. 1964; Ogg and Koslow 1978; Woodley et al. 1981; Rogers et al. 1982, 1983; Kjerfve et al. 1986). The geological effects of hurricanes on upper reefs and beaches, their importance in the formation of boulder ramparts or in the distribution of sediments were also well investigated (Blumenstock 1961; Ball et al. 1967; Baines et al. 1974; Flood and Jell 1977; Hernandez-Avila et al. 1977).

Diving surveys on outer reef slopes around several islands of French Polynesia during September and October 1983, subsequent to the hurricanes which devastated the South Pacific region between December 1982 and April 1983, revealed that coral destruction could be an extensive and catastrophic phenomenon on atoll outer slopes (Laboute 1985). During the hot season 1982–83, six hurricanes (Lisa: 11–13 December 1982; Nano: 20–27 January 1983; Orama: 22–27 February 1983; Reva: 6–14 March 1983; Veena: 7–13 April 1983; William: 15–21 April 1983) ravaged French Polynesia (Fig. 1). Their mean characteristics were the following ones (maximum values in brackets): central storm pressure = min. 950 hPa; max sustained wind speed = 45 m/s (62 m/s); radius of maximum winds >28 m/s = 100 km (150 km); mean sea level change (storm surge) = 2–3 m (4 m); local wave height = 8–10 m (12 m) (Services Météorologiques Pacifiques 1983). Hurricanes intensities and tracks were similar to those registered for hurricanes of the early century (1903–1905) which wrought catastrophic damage to Polynesian islands. On the contrary, tropical storms and hurricanes occurring in French Polynesia between these

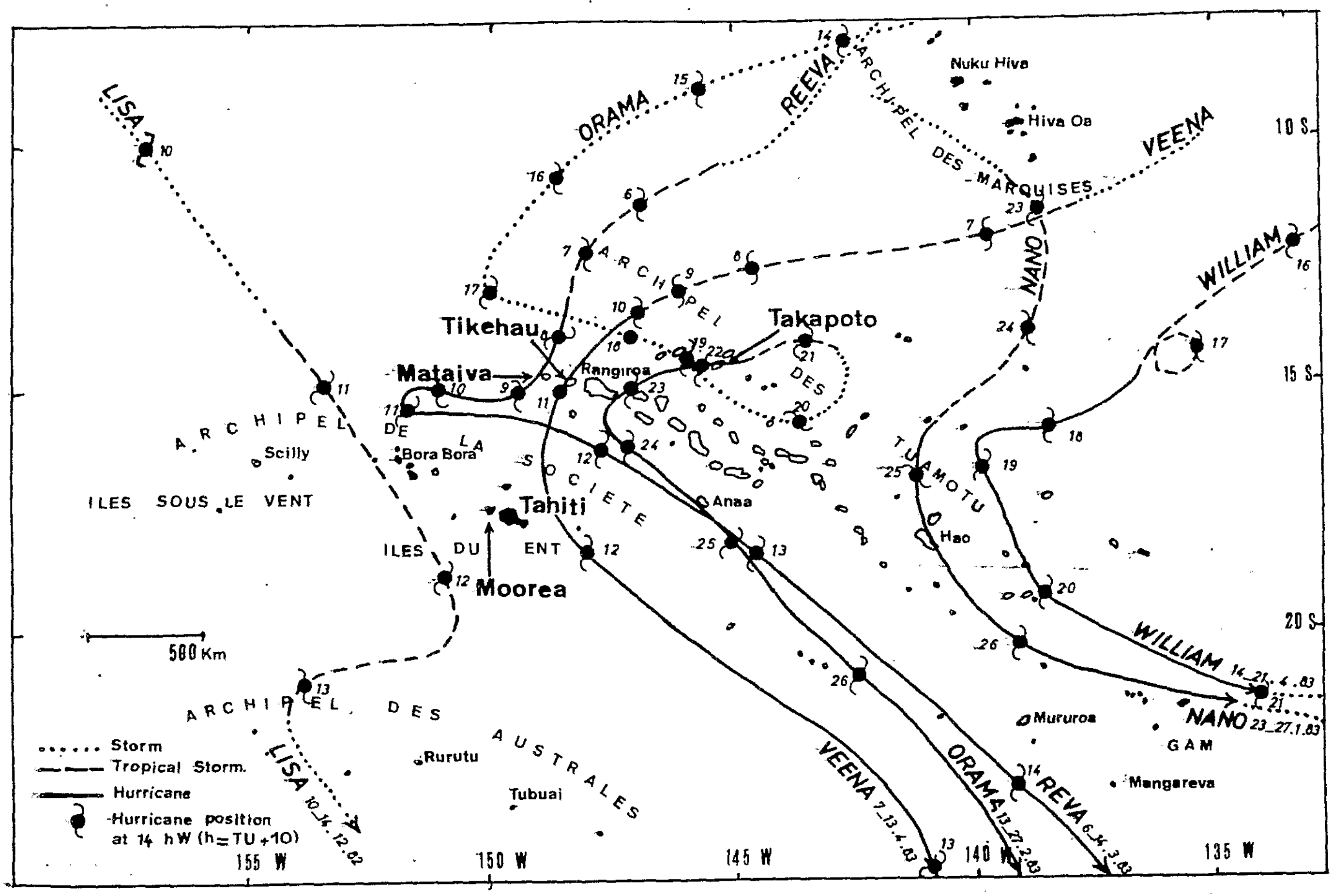

Fig. 1. Tracks of the six hurricanes which ravaged French Polynesia between December 1982 and April 1983 with location of survey islands (Tikehau, Takapoto, Mataiva and Moorea) (After Service Météorologique du Pacifique, 1983)

two periods (mainly from 1966 to 1978) belonged to an other system shifted westward from about 10 degrees, affecting the Cook and Austral Islands (Doumenge 1984). Three of them (Orama, Reva and Veena) seriously affected the atoll of Tikehau, Tuamotu archipelago (15° S, 148° 10 E) (Services Météorologiques Pacifique 1983; Auzeneau and Darchen 1983). Veena's eye passed directly over this atoll moving in a south-west direction Winds reaching 200 km/h devastated the village Tuherahera and wide areas of coconut groves. In and outside the lagoon, reef formations suffered severe damage due to strong physical disturbances and high breaking waves (up to 9 m height on the outer reef front). Post-hurricane studies were conducted particularly on the west coast of Tikehau where quantitative data on Scleractinians (Faure and Laboute 1984), reef cryptofauna (Peyrot-Clausade 1984) and fishes (Harmelin-Vivien 1984) were previously collected in October and November 1982, immediatly prior to the impact of the hurricanes. Additional diving surveys were conducted around Takapoto, Mataiva and Moorea islands (Fig. 1) where intensive studies were previously conducted (Salvat et al. 1972; Salvat 1981; Delesalle et al. 1983).

Damage to coral formations

Relevant observations led to the conclusion that hurricane-induced damage on outer coral reef slopes greatly differed with the width of the fore-reef terrace and the angle of the slope.

Damage on steep slopes

On the west coast of Tikehau (Fig. 2), the outer slope can be divided into three morphological zones defined by Faure and Laboute (1984) on the basis of depth range, slope, percentage of coral coverage and physical environmental factors: (1) the shallow fore-reef area (2–10 m deep), (2) a sloping terrace (10–25 m) and (3) the slope itself (beyond 25 m). The western – and leeward – side of the atoll presented a very narrow fore-reef terrace (~ 50 m) and a steep profile (Fig. 2). According to quantitative data recorded by Faure and Laboute (1984) prior to the hurricanes, pre-storm percentages of living coral coverage of the shallow fore-reef area ranged from 5 to 25% in the spur and groove zone (0–4 m) and from 40 to

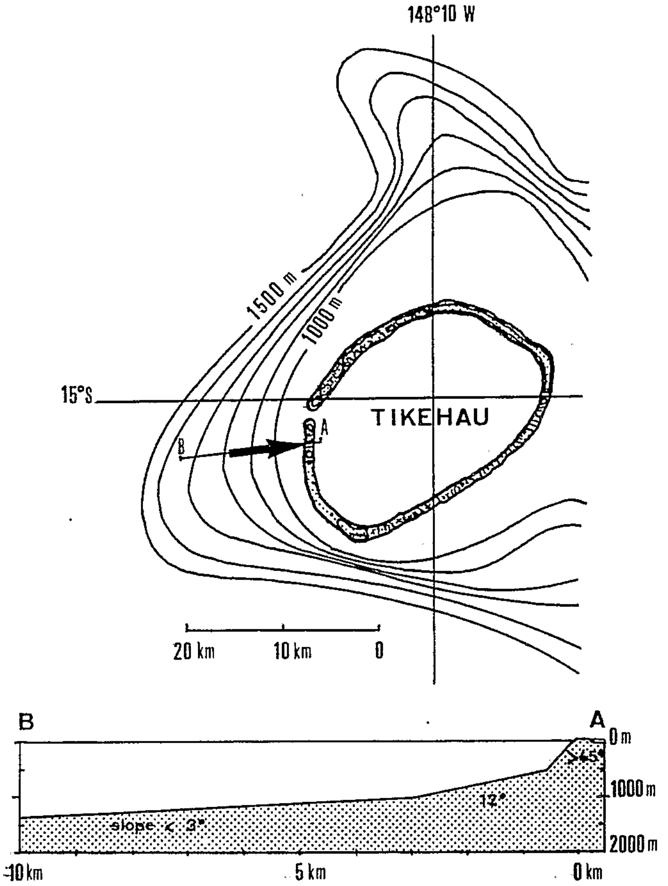

Fig. 2. General map of Tikehau atoll (Tuamotu Archipelago) with location of study site (arrow); A and B = deep profile (0–1350 m) of the west island slope of Tikehau

60% between 4 and 10 m (Fig. 3). Beyond 10 m on the sloping terrace down to 90 m on the slope, and certainly deeper, coral cover varied from 60 to 75% (Fig. 5 and 7). Post-hurricane surveys on this Tikehau outer slope showed that coral destruction ranging from 50 to 100% increased with increasing depth contrary to observations recorded elsewhere on outer reefs (Randall and Eldredge 1977; Woodley et al. 1981). On the Tikehau transect, deeper zones were more severely affected than shallower ones but the cause of coral destruction differed with depth. The shallow fore-reef coral community composed of small colonies well adapted to high energy level environments suffered less than well-developed deeper reef communities. Between the surface and 6 m, coral destruction, estimated at 50%, resulted essentially from abrasion by dislodged material, rolling fragments and scouring sand. A narrow erosional trench, 0.2 to 0.8 m deep, appeared at 6 m on the fore-reef resulting probably from the pressures and shock strength inflicted on the whole reef by high breaking waves. On the sloping terrace, more than half of coral colonies were broken and dead (Fig. 4). Accumulations of dead blocks and fragments occured locally between 10 and 15 m. The most severe damage was inflicted on the well developed but more fragile colonies growing at greater depths. Estimated coral destruction ranged from 60 to 80% between 15 and 30 m; most of the colonies were levelled in this region. Surviving coral patches more than 1.5 m high formed narrow buttresses perpendicular to the reef front separated by wide areas of devastated rubble (Fig. 6). Beyond 35 m to at least 90 m, the lower limit of our observations, where earlier living coral coverage reached 75% (Fig. 7), deep communities dominated by *Pachyseris speciosa* were totally destroyed leaving a levelled detrital zone covered with dead broken coral, rubble and coarse sand (Figs. 8–10). Large heads of *Porites lobata* that are usually numerous between 20 to 40 m had disappeared although some were found broken at depths down to 60 m. As these heads rolled down they were probably responsible for shattering the platy colonies of *Pachyseris speciosa* (Fig. 7). Severe damage was similarly observed deep on the south-east coast of Takapoto and all along the northern and north-eastern coasts of Mataiva, two other atolls with steep outer slopes surveyed during the same trip to Tuamotu.

Damage on low-angle slopes

On low-angle slopes (<25°) as on the north-east coast of Moorea (Fig. 12), damage occurred only between the surface and 18–20 m, a situation that has been generally reported for other reefs (Woodley et al. 1981). Coral destruction was restricted to shallow water where a wide and gently sloping fore-reef terrace of less than 20 m leads to the steep island slope. These conditions were also observed on the northern coast of Tikehau. In these areas most of the broken colonies were thrown up on reef flats or accumulated in boulder ramparts along beaches. These examples appear to indicate that the deeper limit of mechanical destructive action caused by hurricane-induced waves breaking on the reef front is probably located at a depth of about 20 m.

Discussion and conclusion

Highsmith et al. (1980) assessed that survivorship of storm-generated coral fragments is strongly size dependent. Knowlton et al. (1981) have demonstrated that delayed mortality in hurricane-damaged corals could be as severe as the immediate effects of storms and may explain the widely variable rates of reef recovery (e.g. Stephenson et al. 1958; Blumenstock et al. 1961; Stoddart 1974; Mergner 1983). On the west Tikehauan transect all coral fragments were dead and most of the in place coral colonies were extensively scoured by sand and broken coral fragments. It is likely that delayed partial colony mortality due to scour will further reduce the poststorm living coral coverage observed in these zones.

Endean (1976) pointed out that hurricane-driven seas frequently strike the lee side of reefs where there is usually marked development of branching or fragile coral colo-

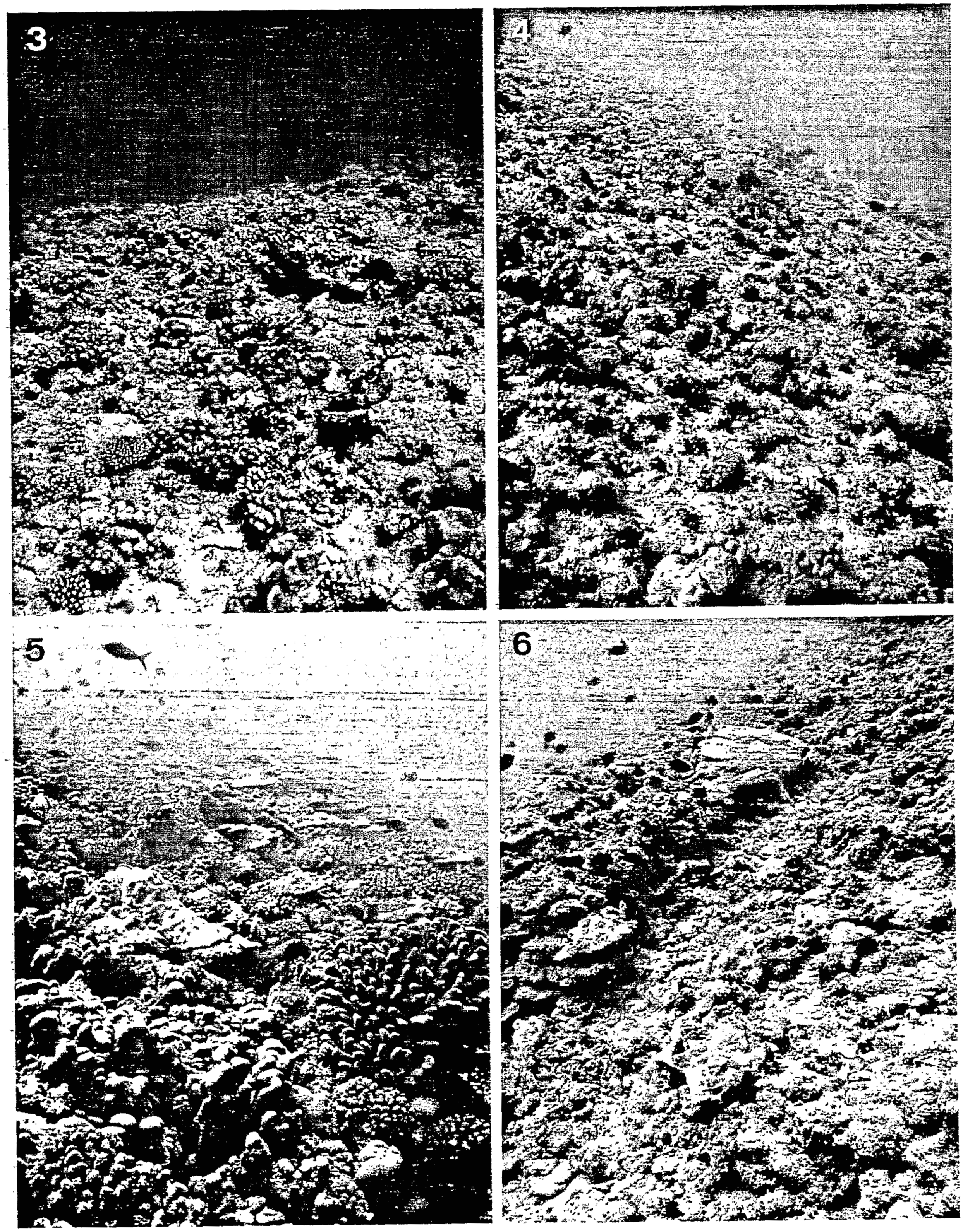

Fig. 3. Tikehau, October 1982: fore-reef area, −6 m, with short and scattered coral colonies well adapted to high energy environment

Fig. 4. Tikehau, October 1983: fore-reef area, −7 m, post-storm physiognomy of this area did not change but many coral colonies scoured by sand and rubble died

Fig. 5. Tikehau, October 1982: flourishing coral community at 20 m on the reef slope

Fig. 6. Tikehau, October 1983: post-storm aspect of the same area at −20 m. Most of coral colonies were broken and levelled leaving a bare slope. Remaining scattered patches occurred between 15 and 30 m

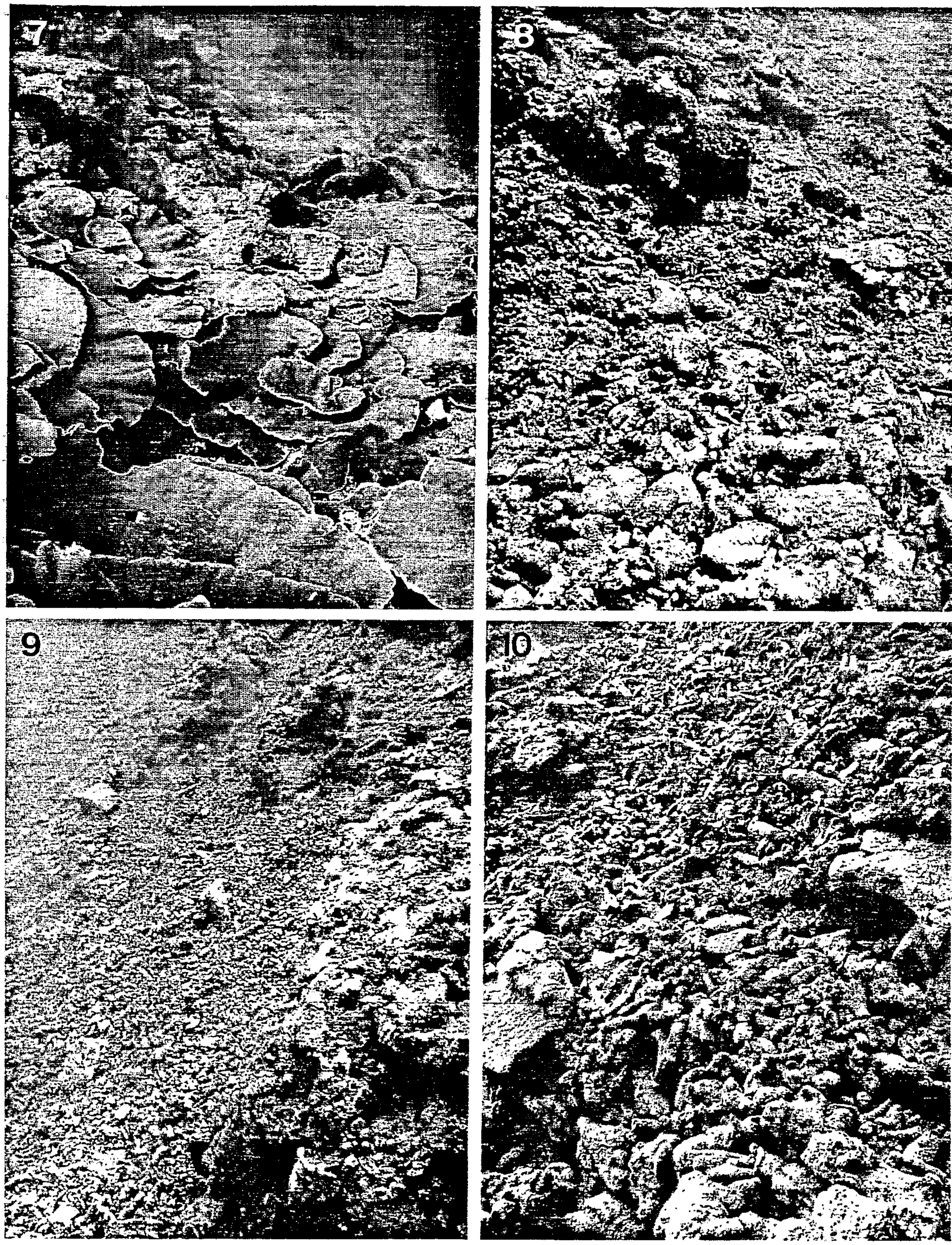

Fig. 7. Tikehau, October 1982: pre-storm aspect of the deep slope (−40 m) with characteristic platelike colonies of *Pachyseris*

Fig. 8. Tikehau, October 1983: post-storm aspect of the slope at −40 m with total destruction of coral colonies deeper than 35 m

Fig. 9. Tikehau, October 1983: general aspect of the slope at −38 m after hurricane damage. Deep coral communities were totally destroyed by an underwater avalanche

Fig. 10. Tikehau, October 1983: detail of accumulation of breaked corals, blocks and rubble on the slope at −38 m after hurricanes

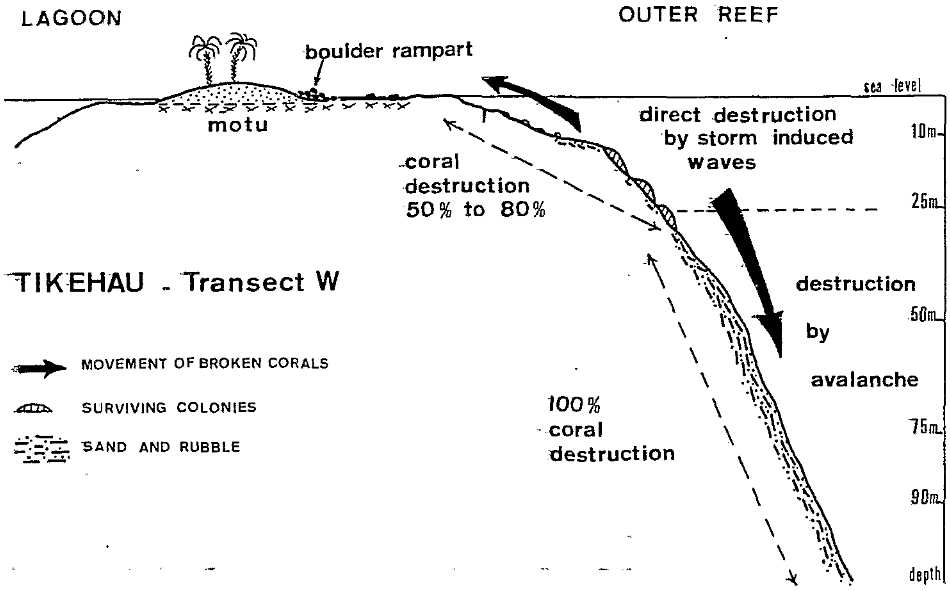

Fig. 11. Cross section of the west coast of Tikehau with explanatory hypothesis of the deep coral destruction: direct coral destruction by storm-induced waves occurred between the surface and −20–22 m. Most of broken corals rolled down the slope breaking deeper colonies. The avalanche process resulting in the total destruction of deep coral communities is generated by a steep slope combined with a narrow fore-reef terrace

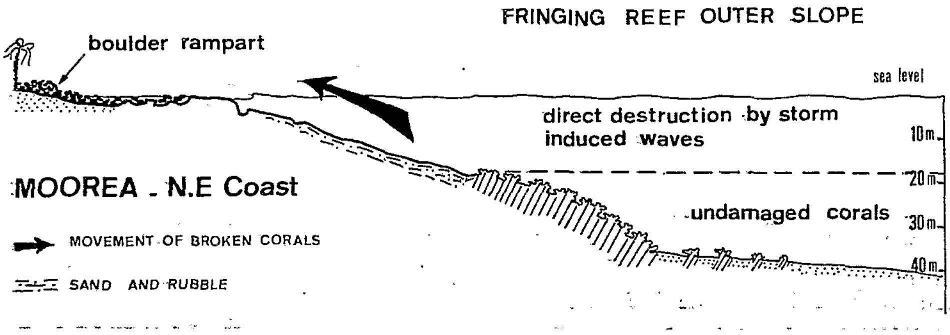

Fig. 12. Cross section of the north-east coast of Moorea. Most of corals broken by storm-induced waves were thrown up on the reef flat or accumulated on the beach. On such a low-angle slope (<20°) coral colonies were undamaged below −20 m deep. The avalanche phenomenon does not occur on gentle slope or when a wide fore-reef terrace extends forward the reef front

nies. Veena's track passed effectively on the lee side (west coast) of Tikehau where coral formations were flourishing (Figs. 5 and 7). This cannot be considered as a general pattern as the windward sides of Takapoto and Mataiva were damaged by hurricanes in 1983. In French Polynesia, windward coasts of the islands are the eastern ones exposed to the trade-winds blowing from NE and SE. On a geological time scale, this phenomenon could perhaps act upon the atoll shape and symmetry. Woodley et al. (1981) and Kjerfve et al. (1986) emphasized the importance of reef profiles including shape, depth and shelf width on the dissipation of waves and types and magnitude of damage. Along the northern coast of Jamaica, they observed that sloping or level reef surfaces were more severely affected than vertical ones and that shallower zones were more damaged than deeper ones. Hurricane damage on outer reefs has been generally reported up to depths of 20 m (Glynn et al. 1964; Hernandez-Avila et al. 1977; Highsmith et al. 1980; Bak and Luckhurst 1980). Randall and Eldredge (1977) noticed some broken coral branches up to 30 m on Guam coral reefs and Woodley et al. (1981) observed a few broken *Agaricia* down to 50 m on north Jamaican reefs. On the contrary, on the western and southern coasts of Tikehau, as in some parts of Takapoto and Mataiva atolls, deep outer reef zones were more severely affected than the shallower ones with coral destruction reaching 100% beyond 35 m. On these slopes an avalanche phenomenon occurred: colonies broken on upper slope areas rolled down the slope, proceeding to break other colonies and creating a chain reaction resulting in massive coral destruction (Fig. 11). Deep-damaged reefs all had a narrow fore-reef terrace and a steep profile (45 to 70°). Both conditions seemed to be required for the formation of deep reef-avalanches. The narrow trough which appeared at 6 m on the west coast of Tikehau indicated that entire reef tracts with their loose inner structure are susceptible to breakage and reworking on a wide scale. Identical but wider and older troughs were observed at 3 m and 11 m on the north-east and south-west coasts of Mataiva.

Generally described as local phenomena (Endean 1976), effects of hurricanes on outer reef formations were impressive from the point of view of magnitude in the Tuamotu. Catastrophic coral destruction affected almost one third to one half of the outer reef slopes of the three atolls recently surveyed: Takapoto, Tikehau and Mataiva. In a few hours, millions of cubic meters of corals rolled down onto the outer atoll slope (in some areas more than 1 m thick coral constructions were levelled) and accumulated probably at depths of between 200 m and 500 m as suggested by the deep atoll profile (Fig. 2 B). Deep submersible dives off the north Jamaican coast have revealed that coarse reef-derived debris were not dispersed but seemed to be restricted to the island slope above 800 m (Moore et al. 1976). Salvat (personnal communication) also observed such clastic reef detritus accumulation mainly at depths ranging from 210 m to 400 m during submersible operations on the island slope off the north-west coast of Tahiti. Massive coral destruction combined with the downward movement of broken colonies may act as an important formation agent of the detrital cone surrounding the atolls, contrary to the Goreau and Goreau (1973) hypothesis which suggested that deposit of catastrophically produced clastics were confined to the shallowest part of the reef and that catastrophies were not the normal means of deep talus production. Although sporadic, such catastrophic phenomena may be of importance on a geological time scale. In the Tuamotu archipelago it has been estimated that an atoll may be ravaged by an hurricane between 4 to 8 times in a century (Auzeneau and Darchen 1983).

The last severe hurricanes that devastated French Polynesia occurred at the beginning of the century between 1903 and 1906 (Giovannelli 1940; Tessier 1969). During February 1906 a severe hurricane affected also the south-west coast of Tikehau, totally destroying the village Tuherahera. Sea level elevation of 3 m and breaking waves of 8 m high were recorded at that time by the inhabitants (Giovannelli 1940; Tessier 1969). Track, intensity and land damage of this hurricane approached those of Reva or Veena. Hurricanes of 1906 and 1983 exhibiting similar characteristics, it could be surmised that the underwater effects, i. e. total destruction of outer reef slope formations, observed for the 1983 hurricane could have been produced by the 1906 hurricane. This hypothesis would suggest that flourishing coral colonies observed in 1982 (Figs. 5 and 7) could not be more than 77 years old. A recovery period of at least 50 years is in accordance with the estimations of Stoddart (1969, 1974) and Grigg and Maragos (1974) for totally destroyed reefs whereas short-term recovery periods ranging from 2 to 10 years were generally attributed to limited reef damage (Stephenson et al. 1958; Blumenstock et al. 1961; Endean 1976; Connell 1973; Shinn 1976).

It should be interesting to follow the aspects of recovery with successional processes of coral recolonisation on Polynesian atoll outer slopes. Will previous communities be restored and, if so, in how many years, or will a new equilibrium be organized increasing the heterogeneity of coral reefs (Connell 1978)?

Acknowledgements. We express our gratitude to Dr. R. N. Ginsburg, University of Miami, for valuable criticisms and helpful comments on the manuscript, to Dr. B. Salvat, MNHN/EPHE Paris and to Dr. A. Intès, ORSTOM Tahiti, for providing us with the opportunity to work in French Polynesia.

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